# ENHANCED OIL RECOVERY USING ALKALINE-SURFACTANT-POLYMER (ASP)

A Senior Scholars Thesis

by

DARYA MUSHAROVA

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2010

Major: Petroleum Engineering

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Approved by:

Research Advisor: Hisham Nasr-El-Din
Associate Dean for Undergraduate Research: Robert C. Webb

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# ABSTRACT

Enhanced Oil Recovery Using the Alkaline-Surfactant-Polymer (ASP). (April 2010)

Darya Musharova
Department of Petroleum Engineering
Texas A&M University

Research Advisor: Dr. Hisham Nasr-El-Din
Department of Petroleum Engineering

Alkaline Surfactant Polymer (ASP) process is a tertiary method of oil recovery that has promising results for future development. It has already been implemented in different areas of the United States such as Wyoming, west Texas, also in Canada and China. The success of this process depends on the proper combination of alkali, surfactant, and polymer and their compatibility with a reservoir. Therefore, the main objective of the proposed research is to identify chemical interactions between ASP chemicals and reservoir fluids and rock.

I hypothesize that testing different alkalis, polymers and surfactants will result not only in getting different profiles of rheological properties of ASP system, but also analyzing compatibility degrees of chemicals with formation fluids and rock properties such as rock wettability, oil mobility and sweep efficiency which will be affected by the designed ASP system. In this paper the results of chemical interactions between ASP chemicals and reservoir fluids are presented and the phenomena occurred are described. The experiments

conducted are considered to be unique for a selected oil sample with certain values of API gravity, viscosity, and chemical composition.

Lab experiments conducted show the effect of polymer, alkali and surfactant addition to an aqueous solution. Polymers were tested with alkali as a function of shear rate for the purposes of the buildup water viscosity in EOR. Different types of alkali at different concentrations are tested for alkali optimal concentration determination. The effect of adding surfactant at different concentrations has been tested, and acidic number of tested oil sample was identified.

Polymers tested with alkali result in non-Newtonian behavior of the testing solution and display a shear thinning beneficial effect for the buildup water viscosity in EOR. The results show that acidic number of crude oil is a critical parameter that affects the optimal concentration for mixing chemicals and interfacial tension profile. The alkali and surfactant added to crude oil result in a significant reduction of interfacial tension and lead to increase of oil mobilization which is a desired output after ASP injection in EOR process.

# DEDICATION

I would like to dedicate my research project to my mother and to the person who helped me and supported me in all situations, who gave me a lot of lessons to learn, and inspired me to get involved in a beautiful world of science, my adviser- Hisham Nasr-El-Din.

# ACKNOWLEDGMENTS

This page is typically used to acknowledge help from your advisor and co-workers. Often support of family and friends is acknowledged. Financial support is usually mentioned here too.

For the work done I would like to say special thank you my advisor, Dr. Hisham Nasr-El-Din, for his help, time to discuss project questions, and advise how to get experimental results in a best way. Also let me thank you Dr. Nasr-El-Din's graduate research group for helping me in my lab experiments, clarifying unknown part of lab procedures, and giving valuable pieces of advise on my project development.

I am planning to join Dr. Nasr-El-Din's graduate team after my graduation. I am looking forward to working on my research paper in the future in order to fully understand chemical interactions which lead to maximized oil recovery and becoming an expert in Alkaline-Surfactant-Polymer flooding.

# NOMENCLATURE

| | |
|---|---|
| $d$ | diameter of the droplet, cm |
| $P$ | speed from the instrument's readout, ms/rev |
| $R$ | refractive index of fluid |
| $T$ | temperature, ºC |
| $\gamma$ | interfacial tension, N/m |
| $\rho$ | fluid density, g/cc |
| $\omega$ | rotational velocity, rpm |

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# CHAPTER I

# INTRODUCTION

Alkaline Surfactant Polymer method is a result of combination three chemicals with individual functions affecting oil flow behavior and flow change in a reservoir. Introduction of alkali to the system results in soap generation by saponification process. As a result, oil becomes mobile, interfacial tension is diminished, and sweep efficiency is greatly increased. The pH of the system is also changed depending on concentration of alkali and surfactant introduced. Commonly used alkali for ASP injection process are NaOH, KOH, and $Na_2CO_3$.Surfactants are surface active components that are added to the system with a purpose of further oil mobilization, interfacial tension reduction, and wettability reversal. Surfactants of different types are available today. Depending on the charge of the head group in a chemical a structure of the surfactant, nonionic, cationic, anionic, zwitteronic and amphoteric surfactants are distinguished. Nowadays, a popular type of viscoelastic surfactants is widely implemented due to accomplishing two critical functions such as viscoelasticity and viscosity buildup of the system. Being compatible with all other types of surfactants and available as 100% active material free of electrolytes, nonionic surfactants have been selected for lab experiments purposes.

Nonionic surfactants are resistant to hard water, polyvalent metallic cations, and electrolyte at high concentration, they are soluble in water and organic solvents,

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This thesis follows the style of *Journal of Petroleum Engineers.*

including hydrocarbons. POE (polyoxyethylate) nonionics are generally excellent dispersing agents for carbon.

After adding a surface-active agent system of two immiscible phases (e.g., heptane and water), it will be adsorbed at the interface between phases, and will orient itself there, mainly with the hydrophilic group toward the water and the hydrophobic group toward the heptane as shown in **Fig.1**.

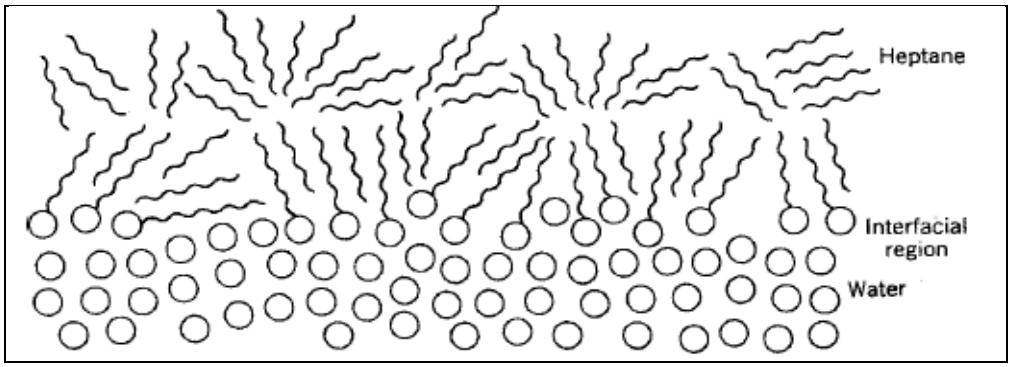



**Fig. 1-Diagrammatic representation of heptanes-water interface with adsorbed surfactant.**

When the surfactant molecules replace water and/or heptane molecules of the original interface, the interaction across the interface is now between the hydrophilic group of the surfactant and water molecules on one side of the interface and between the hydrophobic group of the surfactant and heptane on the other side of the interface. Since these interactions are now much stronger than the original interactions between the highly

dissimilar heptane and water molecules, the tension across the interface is significantly reduced by the presence there of the surfactant (Rosen 2004). The interfacial tension (IFT) can display a dynamic behavior that can be explained according to Borwankar and Wasan (1986) as follows: when the aqueous and the oil phases are in contact, sodium carbonate in the aqueous phase and the organic acids in the oil phase diffuse into the interface, react and produce surface active species. The IFT is a function of the concentration of the active species at the interface. The concentration of these species at the interface depends, among other factors, on their rates of adsorption and desorption. If the rate of desorption is much lower than the rate of adsorption, then the active species accumulate at the interface. This accumulation of the active species causes the IFT to drop significantly. As the concentration of the active species at the interface increases, however, the desorption rate increases, due to the higher concentration gradient present. As a result, the concentration of the active species at the interface diminishes, and the IFT rises again.

Effect of sodium carbonate on IFT of crude oil with polymer and surfactant present was tested in earlier research studies. The results of the experiments are presented in **Fig.2** below. IFT on the alkali concentration as follows: as the alkali concentration is increased, the pH at the interface increases, and the concentration of A- ions increases (acidic components in the oil being HA). The presence of A- ions at the interface causes the IFT to drop to a minimum value.

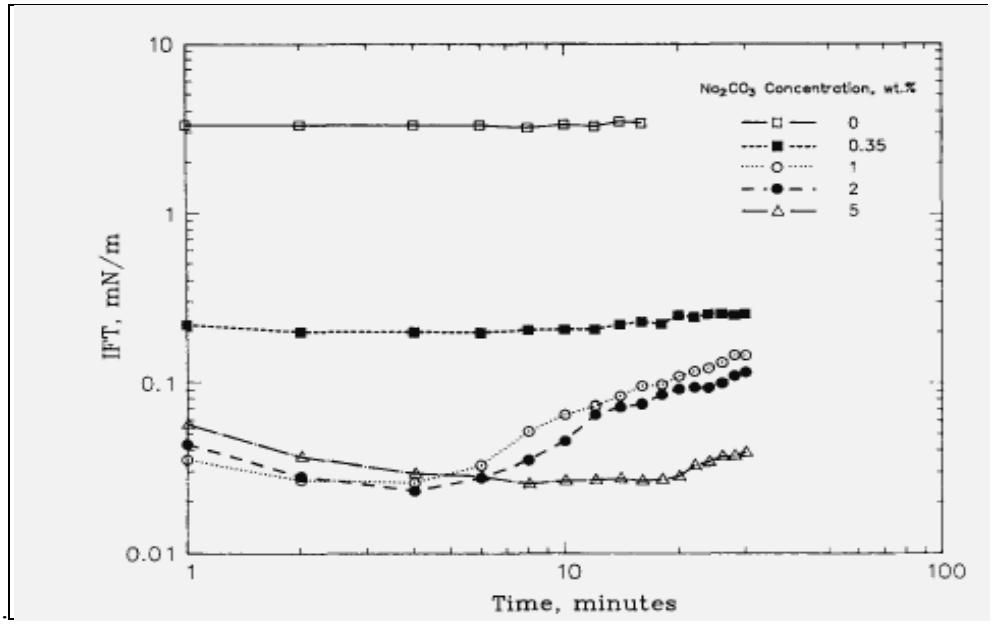



**Fig. 2—Effect of sodium carbonate concentration on interfacial tension. All solutions contain 0.1 wt % polymer and 0.1 wt% surfactant.**

The chemical model of Chan and Yen (1982) can be used to explain the dependence of A further increase in alkali concentration causes a decrease in A- ions at the interface by shifting the reaction to form undissociated soaps (NaA), and as a result, the IFT increases. The effects of several solution variables on low IFT behavior have been determined for some nonionic surfactants. Comparison of these with those of similar studies of anionics (sulfonates) show that nonionics' behavior is (1) much less sensitive to hydrophobe structure; (2) less sensitive to salinity changes; (3) more tolerant to divalent cations; (4) less dependent on alcohol concentration and (5) for some nonionics, pH can be an important factor (Rosen 2004). Petroleum soap is generated by saponification reaction and is mainly applied to the water- soluble.

Soap generated underground by introducing alkali or surfactant to the system is produced mainly by the three different processes:

1. The saponification of neutral oils (triglycerides) shown on **Fig.3**.

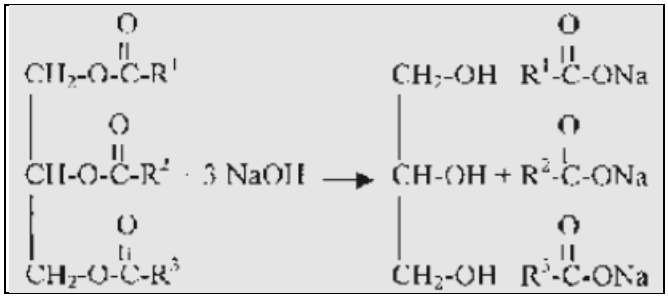


**Fig. 3--Saponification reaction of neutral oils (triglycerides).**

2. The saponification of the fatty acids obtained from fats and oils shown on **Fig.4**

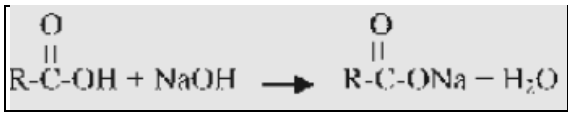


**Fig.4—Saponification reaction of the fatty acids from fats and oils.**

3. The saponification of the fatty acid methyl esters from fats and oils shown on **Fig.5**.

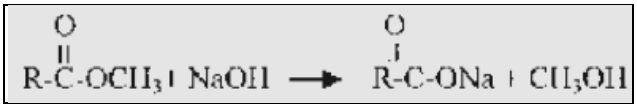


**Fig. 5—Saponification reaction of the fatty acid methyl esters from fats and oils.**

The most important industrial process is the saponification of the neutral oils and of the fatty acids. Both processes may be run in either batch or continuous mode. All types of fats and oils can be used in this process. The most important ones are tallow and coconut oil. The sensitivity of soaps to water hardness is a big disadvantage for many applications. Alkaline flooding (Donaldson et al. 1989 ) has been successfully used to recover waterflood residual oil with acidic crude oils in laboratory- scale experiments. Several mechanisms have been postulated to explain oil recovery by alkaline flooding (Johnson 1976), including low interfacial tension, emulsification and entrainment, wettability reversal, and emulsification and entrapment. Castor et al. (1981) added emulsification and coalescence as an important mechanism in systems which spontaneously form unstable water/oil emulsions.

An important feature in these mechanisms is the presence of acidic components in the oil. These components react with the alkali in the aqueous phase to produce petroleum soaps surfactants) which in turn recover residual oil by one or more of
the above mentioned mechanisms. Despite the success of alkaline flooding in laboratory studies, most field applications were not as successful as anticipated. Some of the

important reasons for the poor field results are alkali loss due to reaction with the rock matrix and hard formation brines, low acid content of the oil, and lack of mobility control, especially with viscous oils. These factors are discussed briefly below.

Alkali consumption by the rock matrix occurs due to silica dissolution, clay transformation and ion-exchange reactions. As a result of the alkali loss, the concentration of $OH^-$ significantly decreases and the efficiency of alkaline flooding diminishes (Krumrine and Falcone 1987). One way to compensate for alkali loss to the rock is to increase the concentration of the alkali in the slug. Using a strong alkali at high concentrations, however, may have an adverse effect on the interfacial tension between the oil and the chemical slug. Also, it enhances rock dissolution (Radke and Ransohoff 1988) and may cause scale formation in the producing wells (Lorenz and Peru 1989). To avoid the adverse effect on interfacial tension when using high alkali concentrations, Nelson et al. (1984) suggested adding a small amount of a synthetic surfactant to alkali solutions. The presence of a synthetic surfactant raises the salinity at which a middle-phase emulsion forms in alkaline flooding.

A second factor to be considered when dealing with alkaline flooding is the acidity of the crude oil. If the oil has a low acid content (i.e., low acid number) then the amount of surfactants produced from the alkali/acid reaction is not enough to significantly lower the interfacial tension (IFT). Synthetic surfactants can be added to alkali/oil systems to lower their IFT (Martin et al. 1988).

Mobility control is a third factor which determines the effectiveness of alkaline flooding in recovering waterflood residual oil, especially with viscous oils (Radke and Ransohoff 1988). A significant increase in oil recovery was observed in many laboratory tests when a polymer was co-injected with an alkali or with alkali/surfactant slugs (Nasr-E1-Din, Hawkins, and Green 1991).

ASP process requires more generalized concepts and deep understanding for a successful application. The success of this process depends on the proper combination of alkaline, surfactant, and polymer and their compatibility with a reservoir that results in the increase of oil mobility and economic benefits due to low chemical losses. As stated above, my research will investigate the process that will identify the interactions between alkaline, surfactant, and polymer, and the way they are to be combined to be compatible with formation for desired output of ASP injection- enhanced oil recovery.

# CHAPTER II

# METHOD

## Effect of surfactant and alkali/surfactant on interfacial tension

*Laboratory procedures*

The two laboratory procedures provide necessary data measurements of interfacial tension (IFT) of a crude oil system with a presence of a nonionic surfactant in one case and an alkali-surfactant mixture introduced to an aqueous solution in another case.

For experiment 1, the main objective was to measure one of the most important properties of surfactants in solution that is a reduction of the interfacial tension. Rather than using alkali which is known for its lower cost and availability for the purpose of oil recovery, we implemented surfactants. This resulted in attaining a lower value of interfacial tension and maintaining it for a longer time than the short time of tension reduction for alkalis.

For experiment 2, we modified the system by introducing sodium hydroxide (NaOH) to the aqueous solution with nonionic surfactant present. When reacting with the acidic components in crude oil and form interfacially active components that accumulate at the oil/water interface and facilitate the formation of oil-in-water emulsion. The stability of this emulsion depends on the concentration of the reservoir formed alkali–oil surfactant at the interface. The amount of natural soap generated is a function of the potential acidic components from crude oil that form interfacial active soap components (Nasr-El-Din and

Taylor 1992). The presence of the synthetic surfactant in the crude oil/alkali system results in lowering IFT compared with the one obtained with alkali or surfactant alone. The surfactant in the crude oil/alkali system may affect IFT behavior in several ways. The surfactant may absorb at the interface, thus lowering IFT significantly, or it may form mixed micelles with the petroleum soaps (Nasr-El-Din and Taylor 1992).

*Materials*

The non-ionic surfactant tests used ethoxylated alcohol, Novel 6-3 Ethoxylate with deionized water. The second experiment used 40 g/mol alkaline sodium hydroxide (NaOH), introduced into the surfactant system in solution with droplet of crude oil inside. The crude oil measured density was determined at 25 °C to be 0.91 g/cm$^3$.

*Interfacial tension measurement (IFT)**

We used University of Texas- 500 spinning drop tensiometer (USA), provided by University of Texas, to measure the interfacial tension between chemical solutions and crude oil at 55 ±1 °C. Glass tubes of 0.24 ml volume and 2mm internal diameter were cleaned with methanol and deionized water. The oil drop was 1.0 µl, dispensed using a 10 µl Hamilton syringe into a glass tube containing the aqueous solution. The tube, containing the aqueous solution and the oil droplet, was then placed in the instrument, and accelerated to a constant rotational speed, after what measurements of the oil droplet shape (droplet diameter) were recorded. The measurements were carried out at 4,070, 5,500, and 6,700 rpm velocities of the tensiometer.

*The section is applicable for all conducted experiments described in this thesis.

Where the ratio of the drop was greater than 4.0, only the diameter was used to calculate the IFT, following the Vonnegut method:

$$IFT = \frac{\Delta\rho\omega^2 R^3}{4} \quad \text{.....(1)}$$

Refractive indices of water (1.33), surfactant (1.45), sodium hydroxide alkali (1.41), and sodium carbonate alkali (1.5) were taken into account. Densities for calculations were taken to be 1 for water, 0.73 for decane, 2.13 for NaOH, 1.01 for ethoxylated alcohol, and 2.16 for $Na_2CO_3$. The speed counter on the spinning drop in milliseconds (v(cycles/sec)=$10^3$/P (ms/rev)), the equation is modified to:

For Experiment I, part A,

$$\gamma = 0.48 * 10^{-6} * \frac{\Delta\rho d^3}{P^2} \quad \text{.....(2)}$$

For Experiment I, part B,

$$\gamma = 0.42 * 10^{-6} * \frac{\Delta\rho d^3}{P^2} \quad \text{.....(3)}$$

For Experiment II,

$$\gamma = 0.46 * 10^{-6} * \frac{\Delta\rho d^3}{P^2} \quad \text{.....(4)}$$

For Experiment III, $\gamma = 0.49 * 10^{-6} * \frac{\Delta\rho d^3}{P^2}$ .....(5)

where d is the diameter of an oil droplet in cm, P-speed from the instrument's readout (in ms/rev), and Δρ is the density differences between water and oil drop. The values taken for densities were 1 g/cm$^3$ for water and 0.73 g/cm$^3$ for decane (Δρ=0.27) (Cayias et al.).

**Experiment I. Part A. Effect of surfactant alone on IFT**

For the experiment 1, we added nonionic ethoxylated surfactant alone and measured IFT.

**Experiment I. Part B. Effect of alkali/surfactant on IFT**

For experiment 2, we prepared an aqueous solution of surfactant and alkaline mixture. The alkaline was NaOH, originally in a solid form. We stirred the alkaline-surfactant solution with a magnetic stirrer for 10 min at 25 °C until NaOH was totally dissolved in solution. The ready solution was soapy and denser in comparison with solution prepared for the first experiment, water with surfactant mixture. The solution was introduced into a glass tube being cleaned by alcohol and deionized water, and then oil droplet was injected. The tube was placed inside the tensiometer device and the system was turned on rotation speed of 4,070 and later on 6,700 rpm. Observations showed that the time for the droplet elongation was longer in a water/alkali/surfactant solution than in water/surfactant system only. The IFT was calculated using Eq. 3.

**Effect of sodium carbonate alkali concentration on IFT**

*Laboratory procedures*

The following laboratory procedure provides necessary data measurements of interfacial tension of a crude oil system with a presence of alkali only. The alkalis are commonly applied in chemical flooding in petroleum industry. They are known for its lower cost and availability for the purpose of oil recovery.

*Materials*

Crude oil sample by Chem technologies was used for the experiment. The alkali used was sodium carbonate with MW of 105.99 g/mol. The aqueous solution was prepared at

different concentrations of alkali with a droplet of crude oil inside. The crude oil measured density was determined at 25 °C to be 0.91 g/cm$^3$.

*Interfacial tension measurement*

The experiment objective was to see the effect of sodium carbonate alkali added to crude oil sample. The crude oil IFT was measured as the alkali concentration was increased gradually. The procedure of IFT measurements is described on page 10. The recorded data measurements were used to calculate IFT using Eq. 4 in IFT measurement section above on page 10.

**Experiment II. Effect of sodium carbonate alkali concentration on IFT**

To recall from the earlier experiments conducted, after alkali is added, it reacts with the acidic components in crude oil and form interfacially active components that accumulate at the oil/water interface and facilitate the formation of oil-in-water emulsion. The stability of this emulsion depends on the concentration of the reservoir formed alkali–oil surfactant at the interface.

For this experiment, the main objective was to identify the effect of only alkali introduced to the system and to analyze the interfacial tension behavior of the crude oil droplet in the aqueous phase solution with a presence of alkali. Alkali used for the experiment was sodium carbonate $Na_2CO_3$. The starting concentration was 0.05 wt%. Then the concentration was increased to 0.1 wt% and 0.5 wt%. Crude oil IFT was measured at each of the concentrations.

**Effect of sodium hydroxide NaOH on interfacial tension**

*Materials*

Crude oil sample by Chem technologies was used for the experiment. The alkali used was sodium hydroxide with MW of 40.00 g/mol. The aqueous solution was prepared at different concentrations of alkali with a droplet of crude oil inside. The crude oil API gravity was 33 °API.

*Interfacial tension measurement*

The experiment objective was to see the effect of sodium hydroxide alkali added to crude oil sample. The crude oil IFT was measured as the alkali concentration was increased. The procedure of IFT measurements is described on page 10. The recorded data measurements were used to calculate IFT using Eq. 5 in IFT measurement section above on page.

**Experiment III. Effect of sodium hydroxide NaOH on interfacial tension**

Addition of alkali is results in its reaction with the acidic components in crude oil and forming interfacially active components that accumulate at the oil/water interface and facilitate the formation of oil-in-water emulsion. The stability of this emulsion depends on the concentration of the reservoir formed alkali–oil surfactant at the interface.

For this experiment, the main objective was to identify the effect of only alkali introduced to the system and to analyze the interfacial tension behavior of the crude oil droplet in the aqueous phase solution with a presence of alkali. Alkali used for the experiment was sodium hydroxide NaOH. The starting concentration was 1wt%. Then the concentration

was increased to 3 wt% with an increment of 1 wt% in concentration. Also alkali concentrations of 2.5 and 2.36 wt% were completed in order to find as accurately as possibly an optimum concentration of alkali required for middle phase emulsions creation for a particular oil sample of 33 °API gravity. Crude oil IFT was measured at each of the concentrations.

The first experiment was carried out for the purpose of determining the effect of sodium hydroxide NaOH of 1 wt% on IFT of crude oil.

**Total acid number (TAN) of crude oil determination**

For Exp. I and Exp. II the crude oil was tested on acidicity that is done by determining the total acid number (TAN) of crude oil. This lab experiment is very important for the design of the chemical flooding, because the amount of alkaline used for the chemical flooding is proportionally depends on a number of acidic oil groups containing in the crude oil.

In this method, we used a solution of potassium hydroxide (KOH) in isopropanol ($C_3H_7OH$) to titrate the acidic components of a crude oil. For the titration, the oil is dissolved in a non-aqueous solvent which facilitates the process and eliminates or reduces the formation of precipitate on the electrodes. We used a titroprocessor to produce stable potential readings. Any materials present in the crude oil which are acidic in nature will result in a positive increase in the total acid number. Any materials present in the crude oil which are basic will reduce or eliminate the effect of base titration.

*Scope*

The method is applicable to light, medium, and heavy crude oils. It can be used for heavy oil emulsions if the water content of the emulsion is known or determined. Many light oils have a Total Acid Number (TAN) of zero, while medium viscosity crude oils generally have TAN values of less than one. Heavy oils and bitumen may have values up to about 10 mg of potassium hydroxide per gram of oil.

*Apparatus*

A Metrohm titroprocessor, equipped with 5 mL exchange unit, and a stirrer was used. A pH indicating electrode was used. Deionized water saturated with potassium chloride was used as the filling solution for the calomel electrode.

*Reagents*

Benzoic acid, toluene, chloroform, isopropanol, potassium chloride, and potassium hydroxide. Deionized water used in all experiments.

*Solutions preparations*

We first prepared a standardized solution of potassium hydroxide solution of 0.05M which components with quantities are presented in **Table 1.** We added 1.5 g of potassium hydroxide to 500 ml of isopropanol in a 1 liter Erlenmeyer flask. Then we boiled oil gently with stirring until dissolved, allowed solution to stand for two days keeping it protected from carbon dioxide in the atmosphere by an Ascarite guard tube. After we filtered through a fine sintered glass funnel and stored the solution, protected from carbon dioxide, so that it did not come in contact with cork, rubber, or saponifiable stopcock grease.

| TABLE 1—STANDARDIZED SOLUTION OF POTASSIUM HYDROXIDE (0.05 M), COMPONENTS AND QUANTATIES | | |
|---|---|---|
| KOH | 1.5 | g |
| Isopropanol (isopropyl alcohol) | 500 | mL |

The next solution which we needed for conducting TAN experiment was crude oil solvent which components with quantities are presented in **Table 2**. To 300 ml liter of toluene we 150 mL of chloroform and 150 mL of isopropanol in a one liter container, and added 9 mL of deionized water and shake well.

The titroprocessor was set up using setting parameters s shown in **Table 3**.

| TABLE 2—CRUDE OIL SOLVENT | | |
|---|---|---|
| Toluene | 300 | mL |
| Chloroform | 150 | mL |
| Isopropanol | 150 | mL |
| Deonized water | 9 | mL |

| TABLE 3—TITROPROCESSOR INSTRUMENT SETTING PARAMETERS FOR TOTAL ACID NUMBER ANALYSIS | | |
|---|---|---|
| pause | 60 | sec |
| titration rate | 1.5 | mL/min |
| anticipation | 15 | |
| stop volume | 30 | mL |
| stop pH | 16 | |
| temperature ambient | 25 | deg C |
| EP critical | 8 | |

We titrated 50.0 ± 0.5 mL of the titration solvent using a titroprocessor. Accurately weighted out three samples of benzoic acid of about 2, 5, and 10 mg each on an analytical balance, then added 50 mL of crude oil solvent to each and started titration.

The electrical potential was measured to determine endpoint which is recorded at a point of voltage increase after continuous decrease during a titration process.

*General procedure*

To 10.0 ± 0.1 g of the crude oil in a 100 mL beaker containing a Metrohm magnetic stirring bar, we added 50.0 ± 0.5 mL of the titration solvent. Then immersed the electrodes in the solution, and positioned them to minimize foaming of the mixture.

When we finished titration, we raised the electrodes from the beaker, rinsed with toluene followed by isopropanol and finally deionized water, and immerse the electrodes in deionized water. Each new titration was started in a few minutes.

**Polymer/alkali testing experiment**

The main objective for this experiment was to identify the effect of polymer on the viscosity of the aqueous phase, to identify the effect of alkali addition to polymer system, and to determine polymer/alkali solution behavior with time. To recall, the main function the polymer does is to build up viscosity of the aqueous phase in order to reduce the production of the water and as a consequence increase the oil recovery out of the reservoir. We were tested polymer with alkali in order to see the initial buildup of viscosity, and which effect is done on viscosity profile by addition of the alkali to the aqueous phase with a presence of polymer.

*Apparatus*

The polymer solution viscosity was tested using a viscometer of model M3600 which is commonly applicable for laboratory measurements of viscosity within a range of shear rate from 0.1 to 2010 $s^{-1}$.


**Fig. 6—Viscometer, Model M3600 for measuring solution viscosity.**

*Solutions*

The concentrations of the chemical components used for this experiment are presented in **Table 4.** The polymer tested was provided by Halliburton company, alkali used for testing was sodium hydroxide.

| **TABLE 4—POLYMER TESTING EXPERIMENT** | | |
|---|---|---|
| Mixing time, min | 20 | |
| Temperature of mixing,° C | 20 | |
| **Measurement** | Weight, g | Weight, wt % |
| | 200 | 100 |
| Polymer Halliburton (SGA-II) weight | 0.2 | 0.1 |
| NAOH alkali | 0.2 | 0.1 |
| Water | 199.6 | 99.8 |

*General procedure*

To 0.2 g of polymer was tested in 199.6 g of aqueous solution. The solution enchased by addition of 0.2 g of sodium hydroxide alkali. The solution was mixed until total dissolution of all components at T=20 °C. Then obtained solution was tested to obtain viscosity measurements.

# CHAPTER III

# RESULTS

## Effect of surfactant and alkali/surfactant alone on interfacial tension

*Experiment I. Part A. Effect of surfactant alone on interfacial tension*

The graphical results are displayed in **Fig. 7**. The IFT was calculated using Eq. 2. According to data obtained, the interfacial tension drops from max of 6.03 mN/m down to 0.16 mN/m for the time period of 125 minutes. The trend is pretty descriptive and shows the effect of surfactant on interfacial tension behavior. The droplet initially had a spherical form, and with time its shape was changing, the drop was elongating with time at const rotational speed of 4,070 rpm.

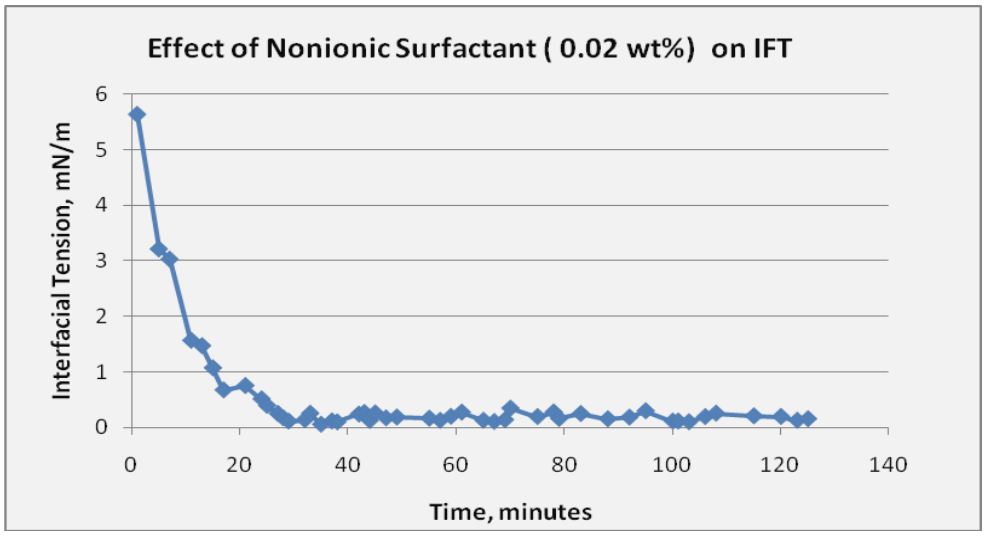



**Fig. 7— Addition of ethoxylated alcohol nonionic surfactant to crude oil/water system induces a significant drop in IFT**

After the system was stopped and the tube taken out, I observed an interesting picture in the tube. The droplet of oil was covered on one side by a layer of a white cloud substance other than water. That appeared to indicate a phase separation in the aqueous solution. After analysis and proper material study as well as discussion with my adviser Dr. Nasr-El-Din the phenomena, my expectation were verified that aforementioned white blurry solution was a result of phase separation of surfactant when surfactant was approaching its cloud point in a heating process.

Change in the Cloud Points of Aqueous Solutions with Nonionic Surfactants

The 'cloud point' is the temperature at which the solution, on being heated, begins to show turbidity because of dehydration of the polyethoxylate (POE) chains, and then starts rapidly to increase (Binana-Limbele, 1991a).

Aqueous solutions of POE nonionics, if the oxyethylene content is below about 80%, become turbid on being heated to a temperature known as the cloud point, following which a separation of the solution into two phases occurs. This phase separation occurs within a narrow temperature range that is fairly constant for surfactant concentrations below a few percent. For both experiments Exp.1 and Exp.2, we used nonionic surfactant of 0.02 wt% . According to the material data safety sheet, the cloud point range for ethoxylated alcohol varied from 30° F (-1.1 °C) to 50°F (10°C).

Glatter et al. (2000) showed that aqueous solutions with a presence of surfactant may lead to micellar growth and increased intermicellar attraction caused by the formation of particles, rodlike micelles which are so large that the solution becomes visibly turbid when

the temperature increases. Nakagawa (1963) showed that the difference in density results in the micelle-rich a micelle-poor phase separation which as we observed, appears to be a case in our solution.

**Fig. 8** shows the crude oil droplet after being spun in a tensiometer in 0.05 wt% auquous solution with a presence of nonionic surfactant It is easy to see the phase behavior of a given solution difference. On one side of the oil droplet, the water-surfactant solution is clear and does not have any effects of abnormal solubility, while on the other hand the solution is unclear, white and not penetrating, meaning that the surfactant displays turbidity.

**Fig. 8—Phase separation of 0.05 wt% nonionic surfactant indicated turbidity from abnormal solubility.**

*Experiment I. Part B. Effect of alkali/surfactant on IFT*

**Fig. 9** shows that IFT declines with time and then starts to increase although it never reaches its initial maximum value of 1.18 mN/m. IFT decreases to the lowest value of 0.65 mN/m, after which IFT increases to 1.47 mN/m value at 112 min. This trend of interfacial tension was observed by Nasr-EL-Din et. al (1192). They show that as alkali concentration is increased, the IFT starts to decrease, reaches its minimum value, and goes up again with a further increase in alkali concentration. The phenomenon of dynamic IFT behavior can be explained as follows: The presence of alkali (NaOH) leads to its reaction with acidic group of the crude oil as a result of which the petroleum soap is generated. The IFT of crude oil/solution system is lowered by adsorption of surfactant at a crude oil/aqueous system interface, thus making the nonpolar (oil) phase more hydrophilic (having a strong affinity for water). The presence of nonionic surfactant as mentioned in introduction will not change the charge of the system significantly, but will tolerate water hardness and pH changes. Nonionic surfactants will also undergo no dissociation process once in water phase. At an exact time of 65 min the IFT will not decrease any more but will go up. It can occur when NaOH concentration is high enough in the aqueous phase what causes the surfactant in the aqueous solution to try to escape from the aqueous phase to locate itself in nonpolar oil phase, thus desorbing from the interface between crude oil and aqueous solution. Hence, IFT will be increased again but at a lower value of initial maximum IFT of the system.

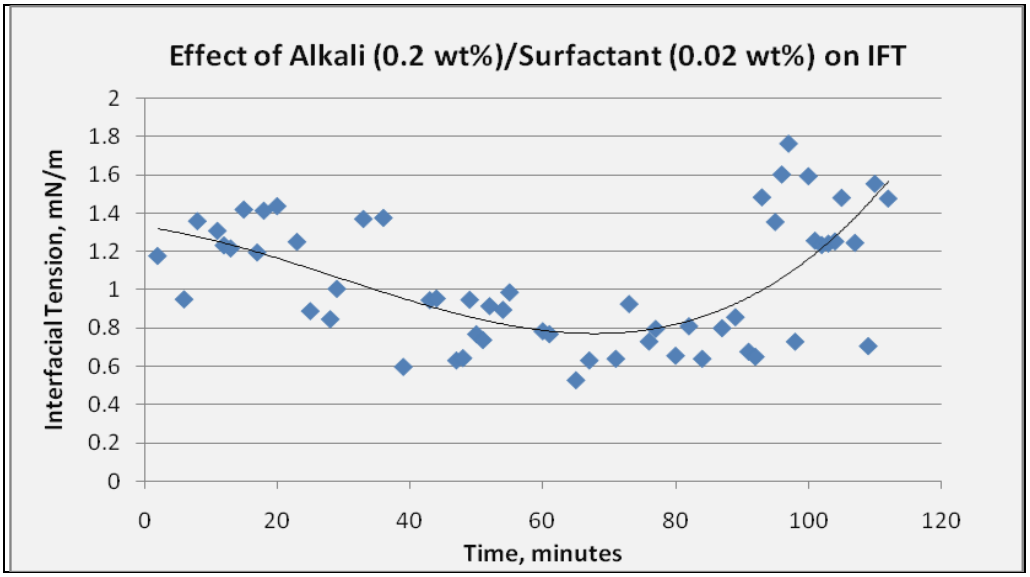



**Fig. 9—Alkali NaOH and nonionic surfactant results in a dynamic behavior of IFT.**

The results suggested that the reason why addition of alkali together with surfactant did not give us the lowest values of IFT is because a specific oil sample we have used for the lab experiments was low acidic. We conducted experiments on total acid number (TAN) determination using a titroprocessor to verify the explanation. Indeed, the acid number was low (0.81mgKOH/mg oil) that shows that the number of fatty acid (oil) groups are small enough what will require a small alkali concentration and a small concentration for surfactant accordingly to produce natural soap though the saponification reaction for oil mobilization. The obtained results for Exp. 2 compare with the ones obtained by Liwei et al. (2008) are presented on **Fig.10** where the effect of active species on crude oil on the interfacial tension behavior of alkali/ synthetic surfactant/ crude oil systems is shown.

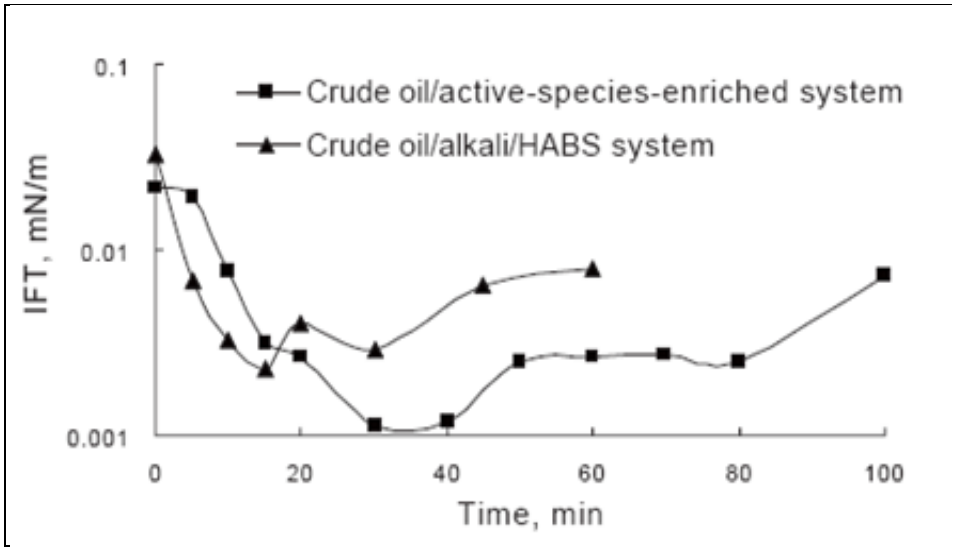



**Fig. 10—Dynamic IFT-time behavior the crude oil /active-species-enriched system and crude oil/alkali/HABS system (Liwei et al., 2008).**

From the resulting plot on **Fig. 11** we see that for the specific crude oil sample that used for the lab experiments, more effects on IFT reduction can be achieved by adding nonionic surfactant of 0.02 wt % rather than for a combination of nonionic surfactant of 0.02 wt% and sodium hydroxide (NaOH) of 0.2 wt%.

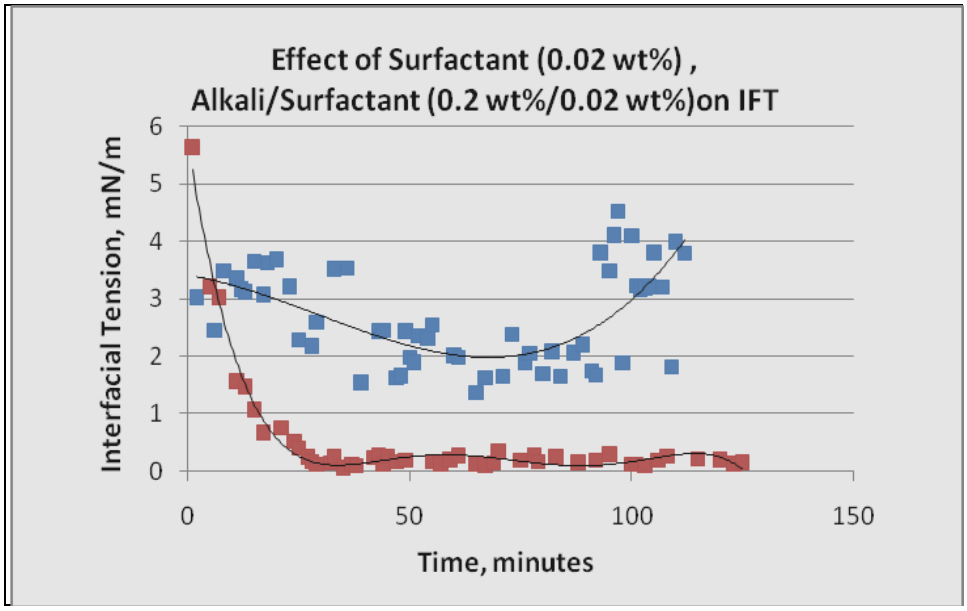



**Fig. 11—Addition of oxylated alcohol nonionic surfactant only results in a significant drop of desired IFT reduction while alkaline/surfactant addition causes IFT to behave dynamically.**

**Effect of sodium carbonate alkali concentration on interfacial tension**

*Experiment II. Effect of sodium carbonate alkali concentration on IFT*

**Fig. 12** displays the results of the conducted experiment when alkali was used at a concentration of 0.05 wt%. The experimental data results show that at the sodium carbonate concentration of 0.05 wt% crude oil interfacial tension has increased from 9 mN/m to the value of 14 mN/m for 60 minute period of time. The analysis of the obtained trend may be caused by two reasons. First of the causes is that the concentration of added sodium carbonate to an aqueous solution is low enough for the natural soap to start to generate by the saponification process. The second explanation of the visualized continuous increase in the interfacial tension values may have occurred in a case when the

alkali—surfactant system which has not reached stabilization state yet during the time the system have been tested.

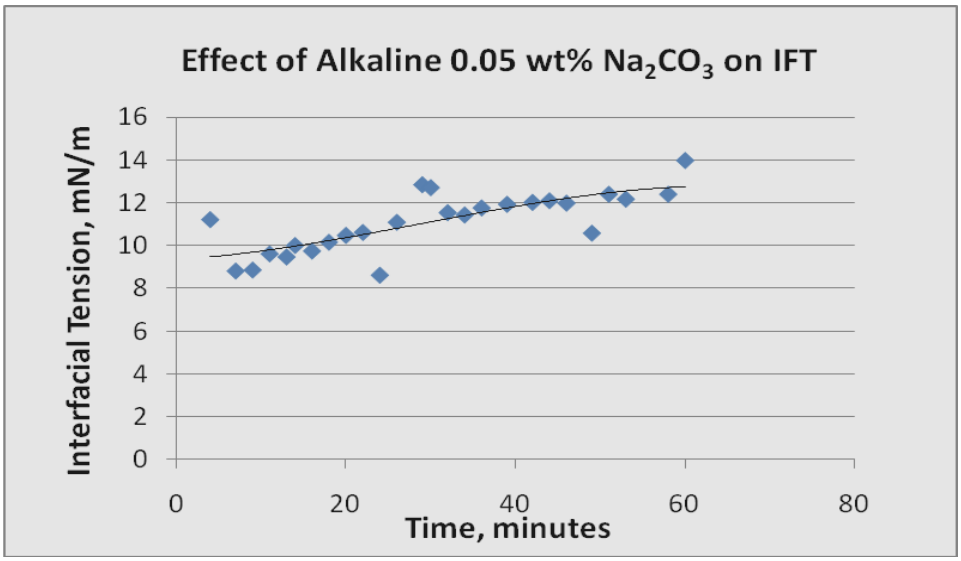



**Fig. 12—Addition of sodium carbonate $Na_2CO_3$ at a low concentration results in an increasing trend in the IFT behavior of the system.**

The next experiment was conducted by increasing sodium carbonate alkali at increasing concentration of 0.1 wt%. The obtained results presented on **Fig. 13** show that at the beginning of the experiment IFT of crude oil rapidly increasing for about 17 minutes. The maximum value of the interfacial tension is recorded to be 3.2 mN/m. The following decrease and approximate stabilization for about 13 minutes are observed and depicted on the graph. The interfacial tension reaches a stabilized value of 1.7-1.8 mN/m. Later, in approximately 6 minutes, the interfacial tension goes up again to a value of 2.3 mN/m, and the IFT decreases again. The general trend displays the dynamic behavior of the IFT trend which has been described in part B of experiment I.

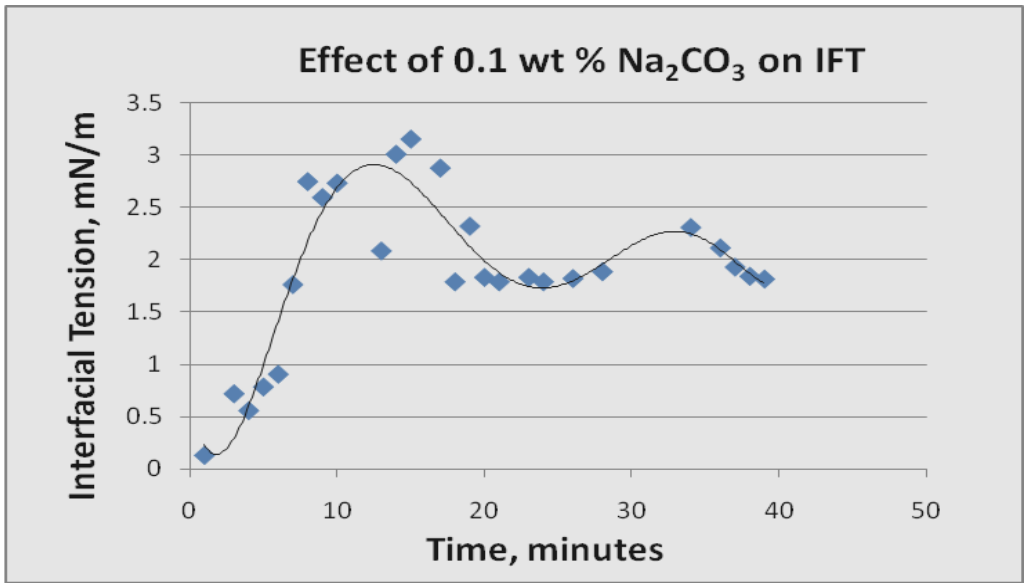
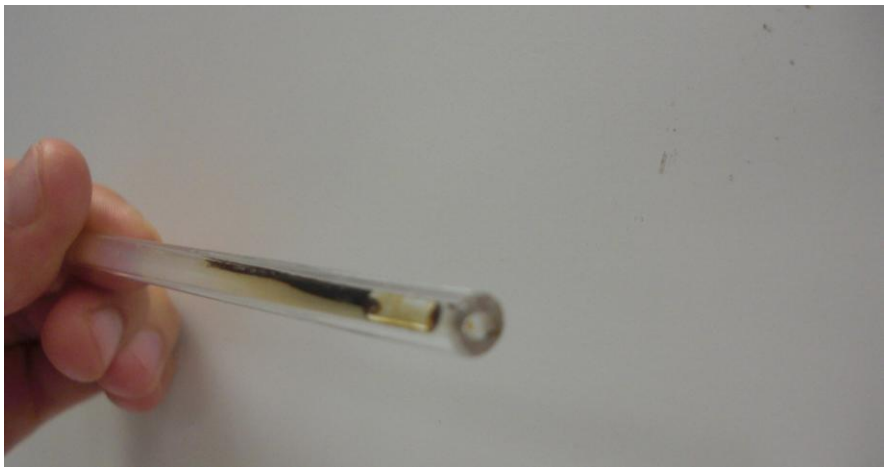



**Fig. 13— $Na_2CO_3$ alkaline displays a dynamic behavior IFT of crude oil.**

The experiment was intended to be conducted at concentration of alkali of 0.5 wt%. However, when 0.5 wt% of $Na_2CO_3$, we could observe the following process: the crude oil was settling down on the walls of the tub, and the alkali solution became blurry due to phase separation of crude oil. **Fig. 14 (a, b)** shows the oil phase separation. The oil droplet lost its round shape, because crude oil acidic components did not react with alkali base so that reaction did not occur, thus no interfacial tension measurements were recorded.

a)



b)

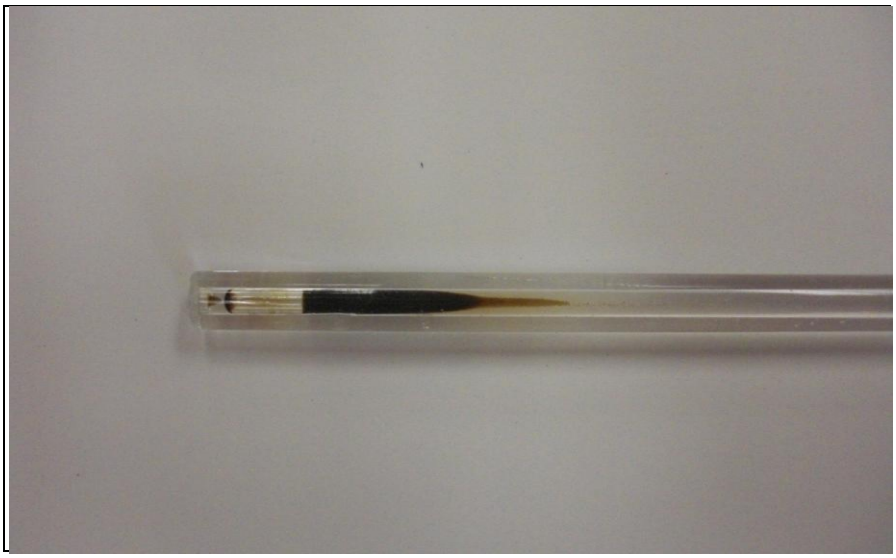


**Fig. 14 (a,b) —Addition of $Na_2CO_3$ sodium carbonate at a critical concentration results in an oil phase separation phenomena.**

Nasr-El-Din et al. (1992) stated that the stability of this emulsion depends on the concentration of the reservoir formed alkali–oil surfactant at the interface. This again depends on the concentration of the potential acidic components from crude oil that form interfacially active soap components when undergoing a reaction process with alkali. As mention above in experiment I, the total acid number (TAN) was determined after a separate conducted lab experiment on TAN for a particular used crude oil sample. The resulted value for the total acid number for the tested crude oil was found to be 0.81mgKOH/mg oil. The proportional stoichiomestric ratio of acidic components of oil and alkaline needed for a successful chemical process of saponification did not appear to be a right one in our case as we observed. Therefore, as the number of oil acidic groups was deficient, natural soap required for oil mobilization, could not have been generated, what resulted in a nonpolar phase dissolution when alkaline present at a critical concentration.

**Effect of sodium hydroxide NaOH on interfacial tension**

*Experiment III. Effect of sodium hydroxide NaOH on IFT*

**Fig. 15** shows the dynamic IFT behavior for 1wt% concentration NaOH equal in an aqueous solution. The nature of dynamic interfacial tension behavior described in the earlier section in part B of Exp. I which showed the effect of alkali/surfactant on IFT was identified and analyzed.

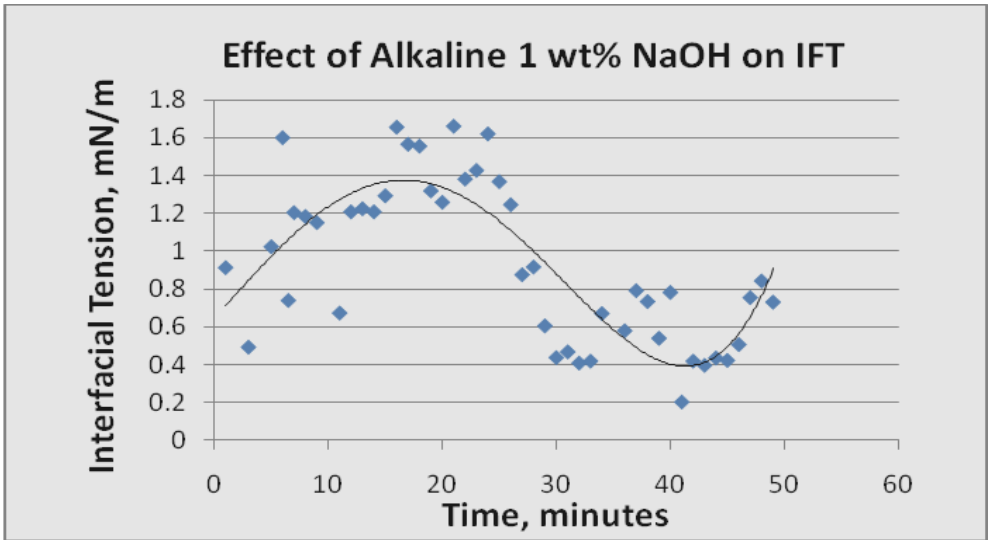



**Fig. 15—Addition of alkali results in a dynamic behavior of IFT.**

The next experiment was conducted to examine the increasing concentration of sodium hydroxide (NaOH) alkali of 2 wt%. **Fig. 16** shows a dynamic behavior of the interfacial tension as in the previous experiment. The phenomenon of this interfacial tension trend is described in the section in the first experiment.

The next concentration of the sodium hydroxide we intended to examine on the interfacial tension was 3 wt%. However, the following observation was visualized: oil was stuck to the tube walls and no oil was mobilized in the tube. The reason for this behavior is that the tested sodium hydroxide concentration was exceeding the optimal one at which IFT attains the lowest value.

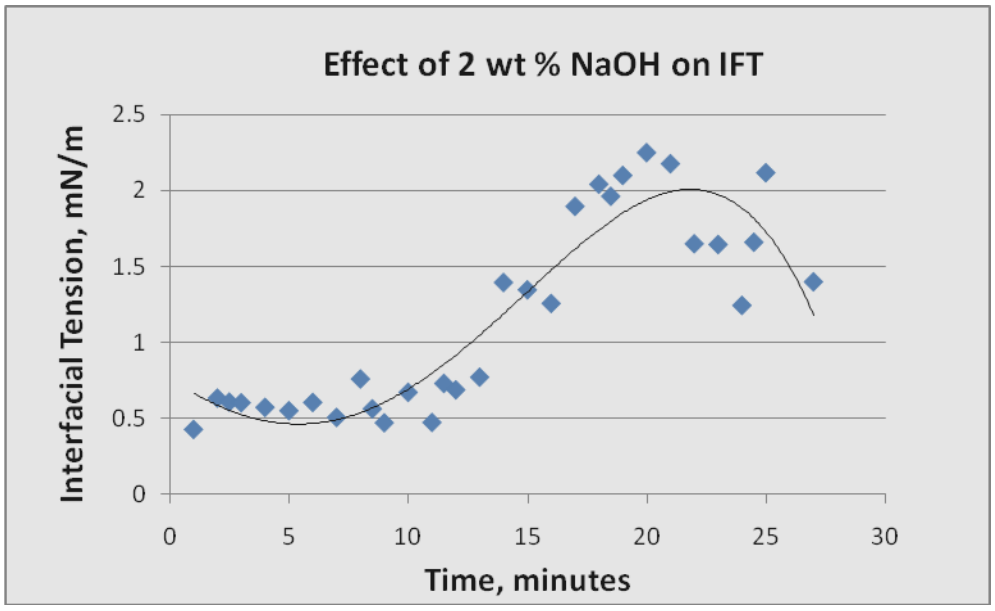



**Fig. 16—Addition of alkali results in a dynamic behavior of IFT.**

We continued the experiment by going back, meaning that we decided to decrease the alkali concentration in order to get as close as possible to the critical concentration of sodium hydroxide for the °API gravity oil sample. The concentration was reduced to 2.5 wt%. This time we observed that very small bubbles of oil were separated from a main mass of crude oil droplet which was still adhered to the tube wall. The effect of segregation of the small bubbles rising up the tube might be caused by the gravity and buoyancy forces acting on small bubbles rising up the tube. The interfacial tension reduction did not take place, because the oil droplet was still attached to the tube walls. The existence of the rising oil bubbles showed us also that we were approaching the optimal concentration at which all oil droplet would be mobilized (detached from the tube walls).The next attempt to reach the least critical concentration was the use of sodium hydroxide alkali at 2.36 wt%. We were able to conduct the test successfully, because we

managed to get all oil lifted in our solution with this concentration of alkali, although this concentration of alkali did not result in getting lower values of the IFT.

**Fig. 17** shows that interfacial tension does not display a clear trend, but has a variation in values in the range from 6 to 10 mN/m. At 2.36 wt% concentration of NaOH, we can observe that IFT dynamic effect still takes place, and IFT values are measured to be higher than for the lower concentrations of NaOH alkali.

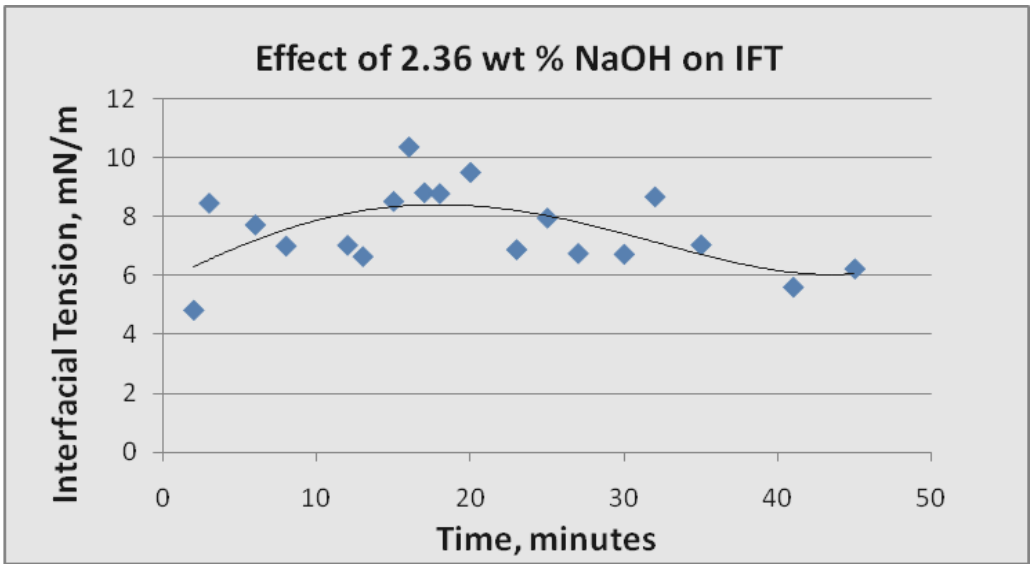



**Fig.17—The obtained closest critical concentration of sodium hydroxide NaOH resulted in fluctuating of IFT values.**

**Total Acid Number (TAN) of crude oil determination**

The procedure of titration for a titrant containing 2.5 mg of benzoic acid is shown in **Table 5** and **Fig. 18**, for a titrant containing 5 mg of benzoic acid is shown in **Table 6** and

**Fig. 19**, for a titrant with 10 mg of benzoic acid is shown in **Table 7** and **Fig. 20**.

| TABLE 5—TITRANION OF CRUDE OIL SOLVENT WITH 2.5 MG OF BENZOIC ACID | | |
|---|---|---|
| **Titrant** | | |
| crude oil solvent | 50 | mL |
| benzoic acid | 0.0025 | g |
| **Results** | | |
| pH initial | 9.76 | |
| pH final | 14.94 | |
| endpoint pH estimated (approx.) | 14 | |
| Volume of titration sol-n KOH (mL) | Electrical Potential measured, mV | |
| 1.5 | -464.2 | |
| 3 | -474.2 | |
| 4.5 | -483.9 | |
| 6 | -491 | |
| 7.5 | -495 | |
| 9 | -495.6 | |
| 10.5 | -497.7 | |
| 12 | -500 | |
| 13.5 | -501.6 | |
| 15 | -502.5 | |
| 16.5 | -503.7 | |
| 18 | -504.2 | |
| 19.5 | -504 | EndPoint, pH≈14 |
| 21 | -504.2 | |
| 22.5 | -503.3 | pH=14.94 |

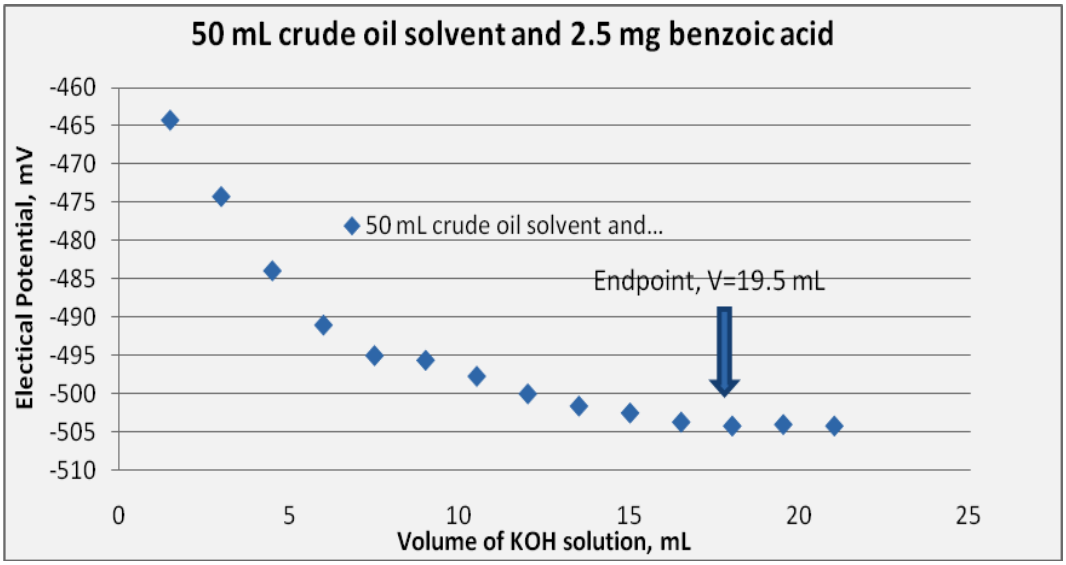



**Fig. 18—Endpoint record for the titration of crude oil solvent and 2.5 mg benzoic acid.**

| TABLE 6—TITRANION OF CRUDE OIL SOLVENT WITH 5 MG OF BENZOIC ACID | | |
|---|---|---|
| **Titrant** | | |
| crude oil solvent | 50 | mL |
| benzoic acid | 0.0048 | g |
| **Results** | | |
| pH initial | 9.57 | |
| pH final | 14.99 | |

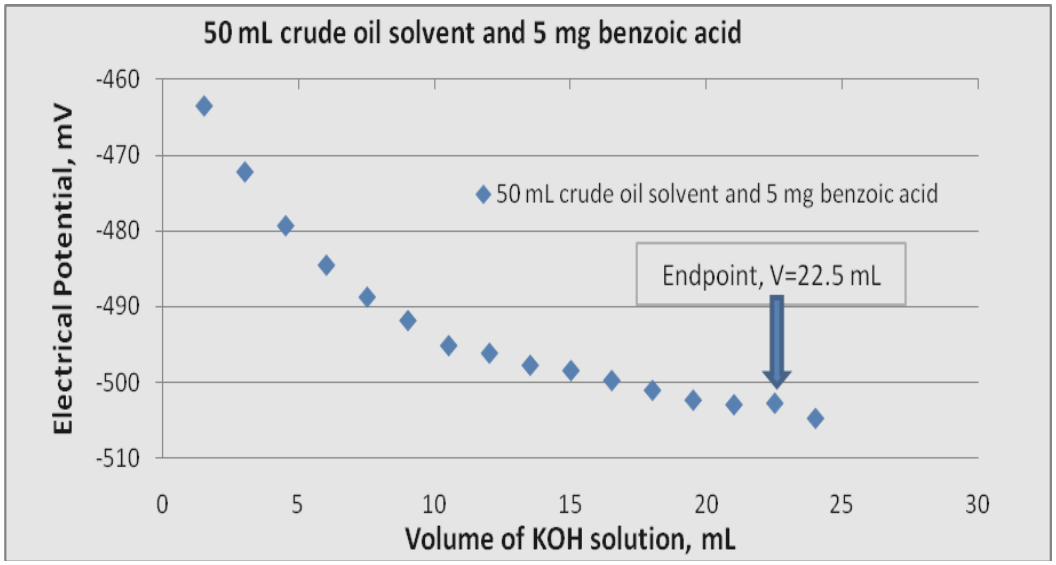



**Fig. 19—Endpoint record for titration of crude solvent and 5 mg benzoic acid.**

| TABLE 7—TITRANION OF CRUDE OIL SOLVENT WITH 10 MG OF BENZOIC ACID | | |
|---|---|---|
| **Titrant** | | |
| crude oil solvent | 50 | mL |
| benzoic acid | 0.0114 | g |
| **Results** | | |
| pH initial | 9.52 | |
| pH final | 14.6 | |

**Fig. 20 shows** that titration in obtaining not a single endpoint. In this case we will make the titration process a little longer after the initialization of the second end point, and record the final value which will be used in calculations.

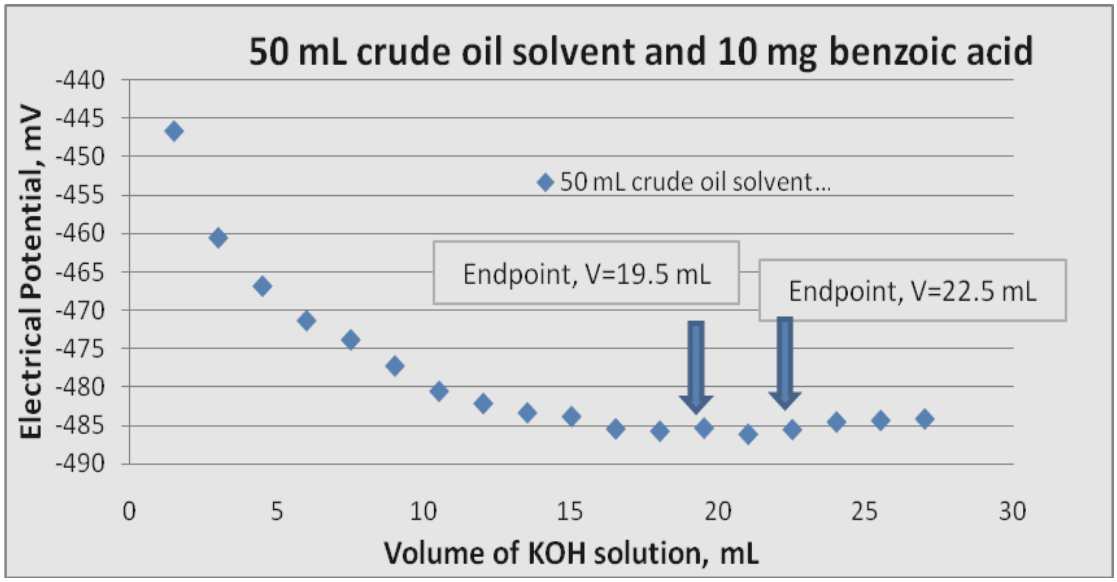



**Fig. 20—Two endpoints records for the titration of crude oil solvent and 10 mg benzoic acid.**

*Calculations*

Blank determination and titrant concentration

Titration of the solvent in the absence of crude oil results in a small but significant blank value. **Fig. 20** shows a plot of titrant required to neutralize the benzoic acid versus the amount of benzoic acid titrated yields two important values. From the y-intercept, an average blank value is obtained. The values are displayed in **Table 8**. From the slope of the line, an average value of titrant molarity can be calculated. As shown in **Fig. 21**, from a least-squares fit the correlation coefficient was 0.99 that showed an acceptable accuracy of the standardization.

| TABLE 8—BLANK VALUE AND TITRATION DETERMINATION | | |
|---|---|---|
| Blank value- y-intercept | 16.6 | mL |
| slope m | 1.18 | |
| slope m → titrant concentration: titrant molarity (moles/L)=1/(m*122.2g/mole) | | |
| **titrant molarity** | **0.0069** | **moles/L** |
| KOH =titrant concentration (mgofKOH/mL) =titrant molarity*56.106 | | |
| **KOH concentration per mL of titrant** | **0.39** | **mgKOH/mL** |

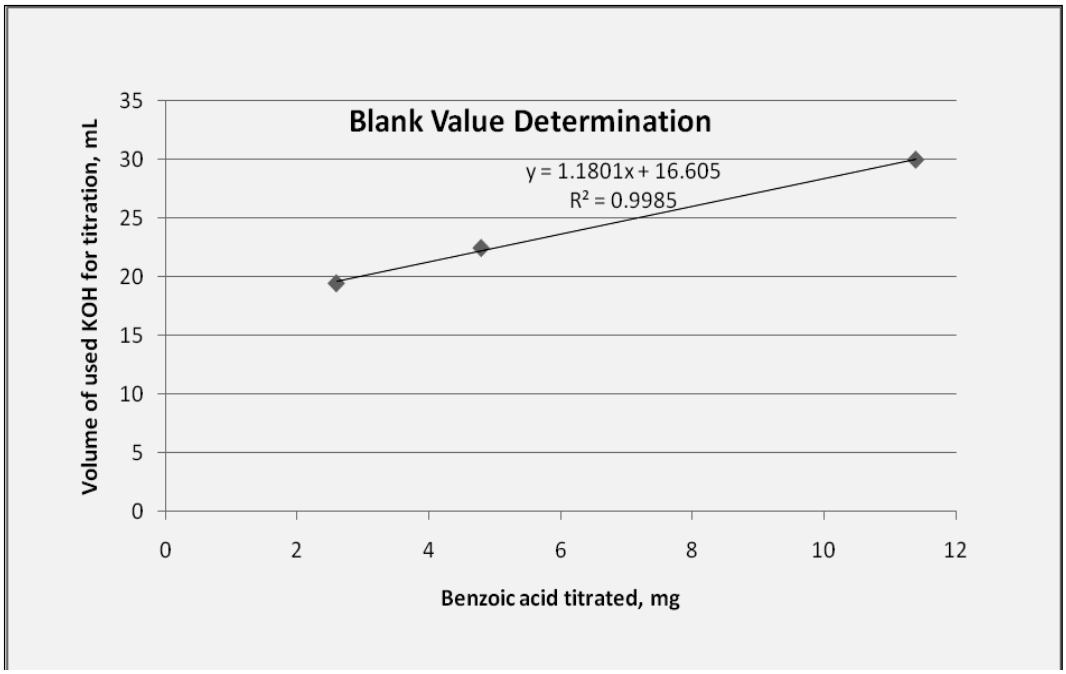



**Fig. 21—Plot mL of titrant to endpoint versus mg of benzoic acid titrated for the bank value determination.**

Total acid number (TAN)

From the titration curve produced by the instrument, the last endpoint that is measured is used to calculate the Total Acid Number. Results are expressed in milligrams of potassium hydroxide required for the neutralization of the acidic components present in 1 gram of crude oil and displayed in **Table 9**.

| TABLE 9—TOTAL ACID NUMBER (TAN) | | |
|---|---|---|
| TAN = ((endpoint(mLs)- blank (mL))* titant molarity*56.106g/mole)/sample (g) | | |
| **TAN** | 0.812 | mgKOH/g of oil |

*Precision and accuracy*

The acidic components of any crude oil are composed of many different structural types, all with differing acidity. This results in titration curves that do not always have clear endpoints. This factor is the largest single source of error in the method outlined here, resulting in reproducibility of $\pm$ 5%. The analysis of the inflection point makes this method more accurate than those that titrate to an arbitrary pH value, because the electrodes are not particularly stable in the non-aqueous solvent that is used.

**Polymer/alkali testing experiment**

Observations were made when mixing the chemicals and stirring them for time of 20 min. First of all, once the polymer was injected, the aqueous phase became very viscous and less movable. Furthermore, the addition of alkali reduced the thick structure of the polymer solution, and resulted in reduction of buildup viscosity.

The results of the polymer testing mixed together with sodium hydroxide alkali NaOH are presented in **Fig.22** for initial time of one day. The viscosity as a function of shear rate equation is show. An initial value of viscosity reaches a high value of 2000 cp order what will make an aqueous phase in the reservoir less movable.

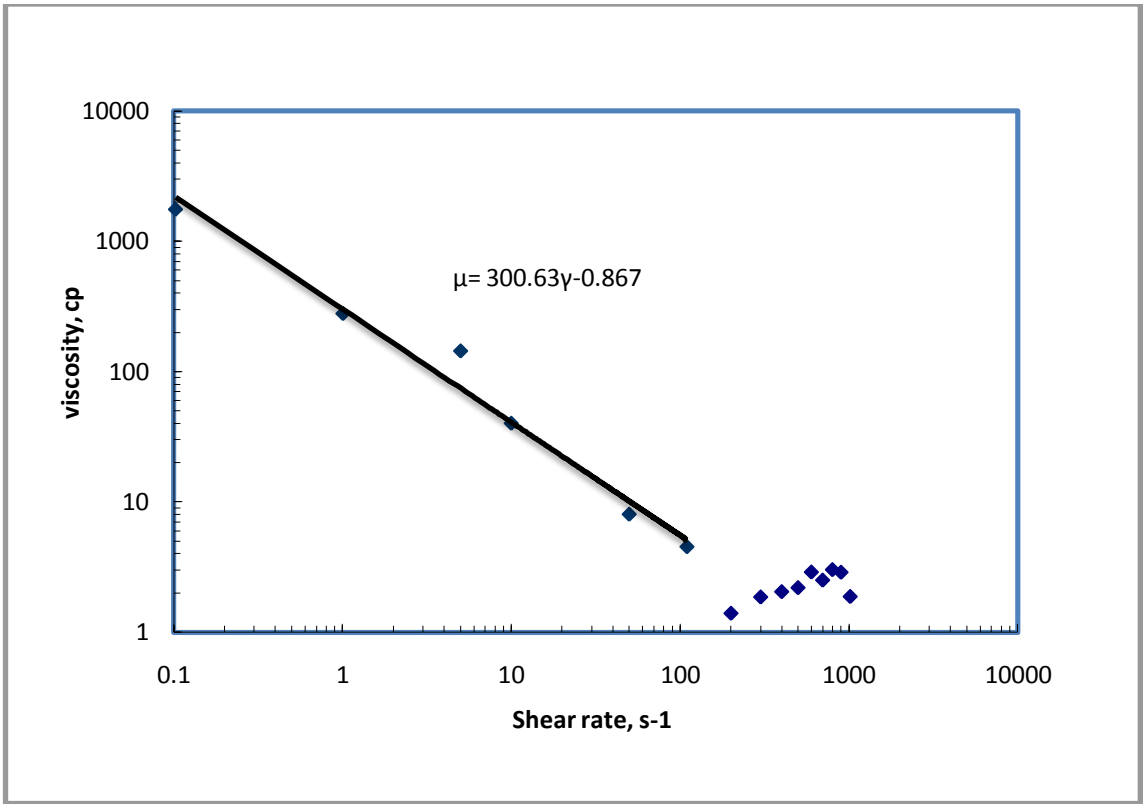



**Fig. 22—Viscosity initial buildup and effect of 0.01 wt% NaOH addition to the system for a one day time period.**

The next polymer testing was conducted to see the viscosity behavior with time. The solution testing was conducted for two days. The solution prepared for the first polymer experiment was stored in a cool closed place with no access to air or factors to prevent the chemical solution change of the initial consistency. The results of the second polymer experiment are combined with the first experiments results of polymer /alkali testing and displayed on **Fig.23.**

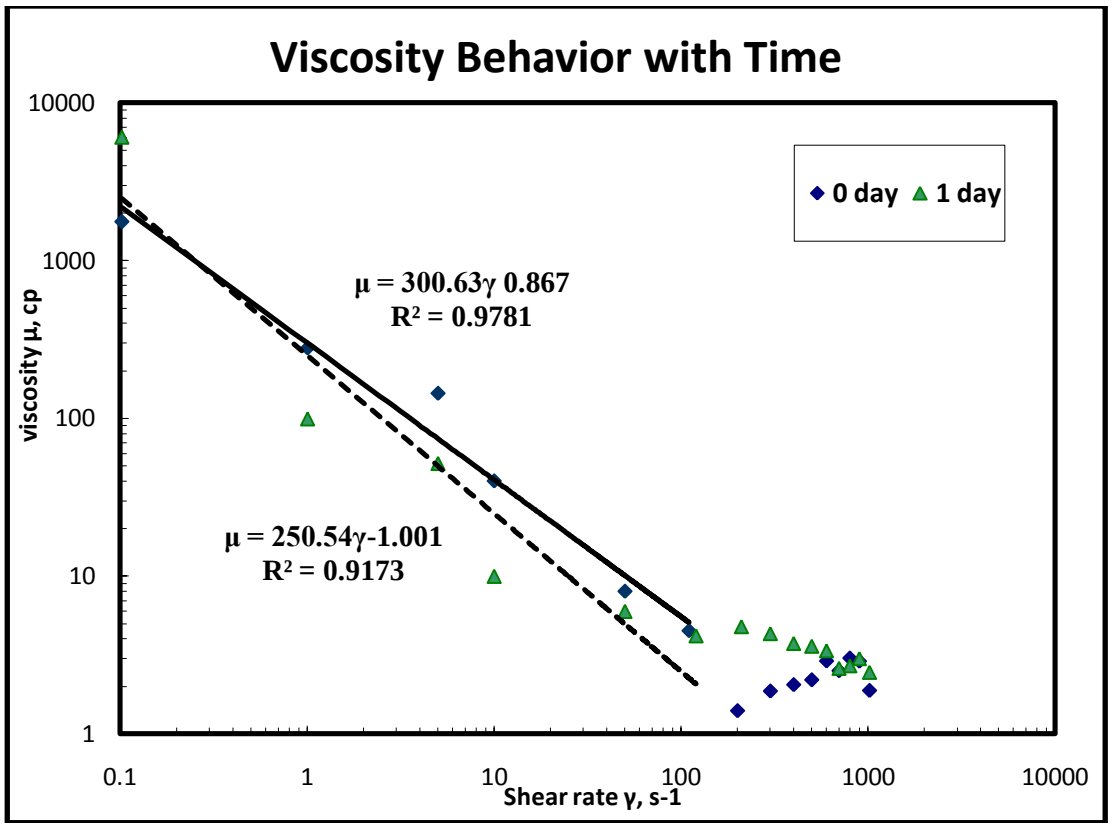



**Fig. 23—Plot mL of titant to endpoint versus mg of benzoic acid titrated for the bank value determination.**

# CHAPTER IV

# SUMMARY AND CONCLUSIONS

## Effect of surfactant and alkali/surfactant on interfacial tension

*Conclusions*

The interfacial tension drops significantly when introducing nonionic surfactant to a crude oil sample. At a certain higher concentration above optimum oxyethylene concentration (critical concentration), crude oil can undergo phase separation. Therefore, from the results of these experiments, the optimal concentration is 0.02 wt% of nonionic surfactant for our tested oil. The mixture of nonionic surfactant and alkali demonstrates a dynamic interfacial tension-time behavior, meaning that the interfacial tension reduction lasts for some time and then comes back to a lower value than for the original one for interfacial tension. The success of compatibility between surfactant and crude oil depends on the right concentration of surfactant/alkali which consequently depends on acidic number of crude oil. An oil sample with a low acid number (0.81 mgKOH/mg oil) will require a small concentration of alkali for a saponification reaction and small concentration of surfactant for oil mobilization. The critical concentration results in a dynamic behavior of IFT, which is not a desired outcome of chemical flooding in a first place. Nasr-El-Din et al. (1991) proposed a solution to minimize and stabilize the dynamic IFT behavior by adding a synthetic surfactant to the aqueous system with the presence of alkaline.

Two interesting observations were made for each of experiments. The first phase separation of the surfactant as it approaches its cloud point temperature at 0.05 wt% surfactant concentration. The second experiment presented the phenomenon of dynamic interfacial tension. From the results, we can see that when adding only surfactant to the system, the interfacial tension is lowered in a greater way than when introducing alkaline to a crude oil /surfactant system. However, if alkaline is added to a water/surfactant system, then interfacial tension may present a dynamic interfacial tension behavior, meaning it starts to decrease, and then at a certain time surfactant desorption from the crude oil/water interface occurs, which results in an IFT increase.

The use of surfactant and alkaline has an important role in IFT reduction that will lead to better oil mobilization and more efficient oil recovery.

*Future research*

As for future experiments, it would be interesting to test different concentrations of surfactants of nonionic surfactants as well as anionic and cationic surfactants and alkali with different types of crude oil samples (light, heavy oils). The ASP system will be examined for compatibility with formation brines and oil for potential emulsion problems. As a result, we believe that testing different alkalis, polymers and surfactants will result not only in getting different profiles of rheological properties of the ASP system, but also will justify a different compatibility with formation fluids and rock properties.

*Recommendations*

For a specific oil sample used to obtain the lowest value of IFT that would last longer, the results of our experiments show that by adding the surfactant of 0.02 wt% concentration,

the IFT in the system will be dropped to the lowest values of 0.16 mN/m, which will not change for a longer time than in a case of both 0.2 wt% alkali and 0.02 wt% surfactant addition. Therefore, for chemical flooding for a reservoir with a tested oil, we would recommend 0.02 wt% surfactant/polymer flooding rather than ASP flooding.

Also, it is very important to test surfactants and alkalis alone and the mixture of both, what will results in getting different IFT profiles for using different crude oil samples with unique characteristics.

**Effect of sodium carbonate alkali concentration on IFT**

*Conclusions*

Three of the performed experiments were aimed to observe the interfacial tension behavior of crude oil as a function of sodium carbonate alkali concentration. The interfacial tension was measured to evaluate the effect of alkali added. The results depicted on **Fig. 24** show that at the minimum concentration of sodium carbonate of 0.05 wt%, IFT was continuously increasing with time. As the concentration of sodium carbonated was increased to 0.1 wt%, the interfacial tension was increasing first and then it was lowered significantly, meaning that the interfacial tension had a dynamic behavior. No interfacial tension was generated at 0.5 wt% of sodium carbonate.

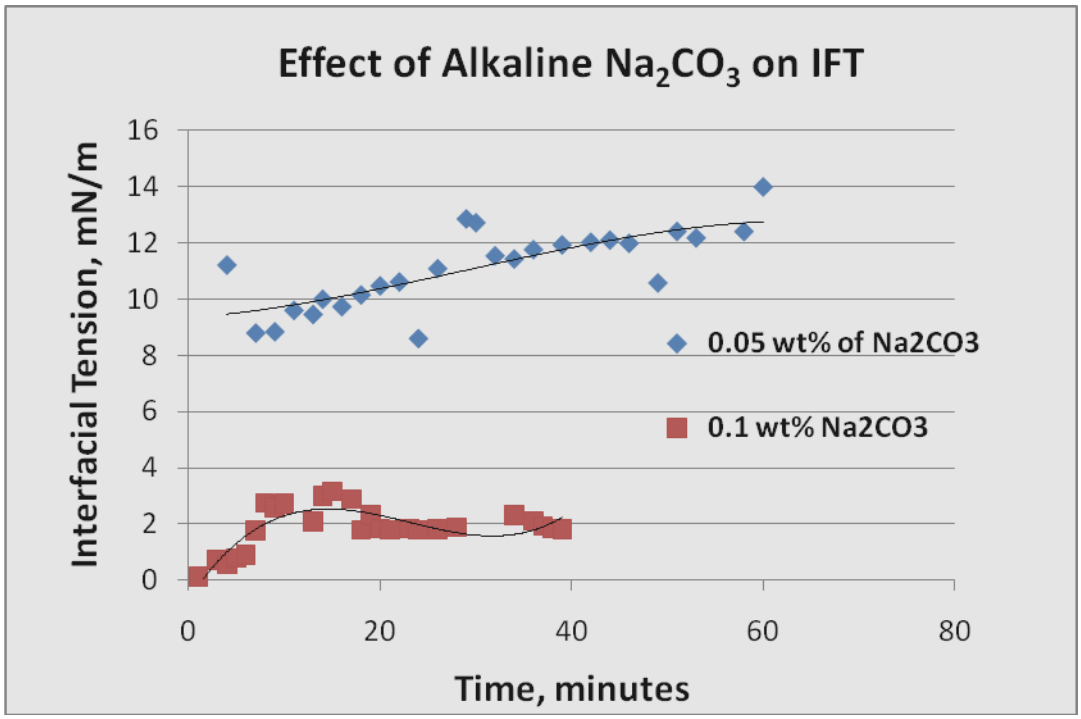



**Fig.24—Testing of alkali at different concentrations results in two different trends for the IFT: 0.05 wt% profile displays a continuous increase of IFT, 0.1 wt% presents a dynamic IFT profile.**

From the obtained experimental results, we can conclude that for a particular oil sample, which was determined to have a low acidity after conducting TAN experiment, the optimal concentration falls into the range of 0.1- 0.5 wt%. Therefore, the experiments proved that low acid oil requires low concentration of alkali.

*Recommendations*

As stated earlier, the alkalis have a broad application in chemical flooding for a purpose of enhanced oil recovery due to their availability, low cost, relative easiness of application, and non-hazardous effect to the environment. However, a very accurate testing is needed

for this chemical, because as the lab experiments results show, there are a few undesired cases which prevent alkali usage or make alkali non-beneficial for the desired outcome that is a largest reduction in interfacial tension of crude oil leading to more efficient oil mobilization in the reservoir. Addition of alkali to an aqueous solution may result in a dynamic IFT behavior, in a continuous increase of the IFT, in reaching a critical concentration (above optimal), when the oil phase separation occurs. In particular, testing on different types of alkalis, on different range of concentration, and the important test of Total Acidic Number (TAN) is to be conducted to obtain accurate data for a further Alkali-Surfactant-Polymer Process.

**Effect of sodium hydroxide NaOH on interfacial tension**

*Conclusions*

**Fig. 25** summarizes all interfacial trends for the experiment of testing sodium hydroxide alkali for a particular oil sample. The critical concentration was determined to be 2.36 wt% of NaOH. We can see that as the alkali concentration was rising, the IFT values were increasing, and the IFT profiles displayed a dynamic behavior. **Fig. 25** shows that the smallest IFT tension is obtained when using NaOH at the concentration of 1 wt% for the crude oil of 33 °API gravity that is beneficial for the oil sweep efficiency in the reservoir.

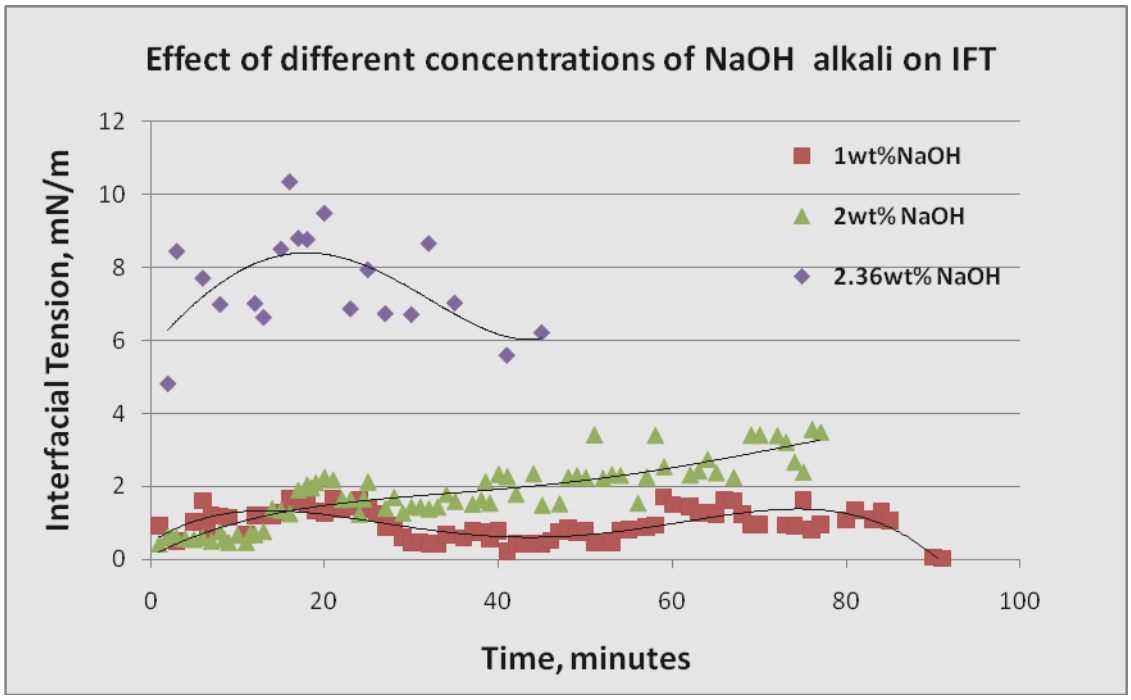



**Fig.25—Generated IFT profiles at different concentrations of sodium hydroxide alkali. As alkali concentration is increased, IFT magnitude goes up.**

Generally, the addition of alkali results in diminishing of the IFT. However, in our case we observe a reverse effect of alkali addition. After analysis and discussion the IFT trends with my advisor Dr. Nasr-El-Din, we may conclude that one of the reason of IFT increase with increasing concentration is that acidic number for this 33 °API gravity oil is probably very low what results in requiring less alkali to neutralize the crude oil and make it movable in porous media due to IFT reduction. Our explanation was further investigated, and the required TAN (Total Acidic number) test was conducted.

**Total acid number (TAN) of crude oil determination**

*Conclusions*

The value for Total Acid Number was calculated to be 0.812 mg KOH/g of crude oil. The analysis of the obtained result for TAN shows that the crude oil has a high basic/low acidic number what will require low alkali concentration in order to generate a desired natural soap by a saponification purpose.

*Recommendations*

TAN laboratory experiment deals with an application of dangerous chemicals which may cause negative consequences if not being used properly. Therefore, the following safety precautions need be studied and implemented.

1. Toluene

Flammable, vapor harmful. Keep away from heat, sparks, and open flame. Keep container closed when not in use, and use adequate ventilation. Avoid breathing vapor or mist, and avoid prolonged or repeated contact with skin. Protective gloves and eye protection are recommended.

2. Isopropanol (isopropyl alcohol)

Flammable, keep away from heat, sparks, and open flame. Keep container closed when not in use, and use with adequate ventilation. Avoid breathing vapor or mist, and avoid prolonged or repeated contact with skin. Protective gloves and eye protection are recommended. Do not take internally.

3. Chloroform

May be fatal if swallowed. Harmful if inhaled. May produce toxic vapors if burned.

Cancer suspect agent. Keep container closed when not in use, and use with adequate ventilation. Avoid breathing vapor or mist, and avoid prolonged or repeated contact with skin. Protective gloves and eye protection are recommended.

4. Sample handling and Waste Disposal

Sample handling and analysis should be carried out in an adequate fume hood. All solvent waste must be disposed of as chlorinated waste.

**Polymer/alkali testing experiment**

The Polymer/Alkali experiments results in very important conclusions for the ASP chemical flooding. First of all, addition of polymer to the aqueous system results in a buildup viscosity of the aqueous phase in a short time. This is a really positive effect for an oil recovery process. The production of the undesired water will greatly be reduced that will have a further impact on the economical saving due to disposal issues and environmental obligations. Secondly, the polymer addition to an aqueous system changes the behavior of the fluid. Water being a Newtonian fluid is converted to a non-Newtonian fluid meaning its viscosity is not being equal to constant of 1 cp (centipoise). The next important conclusion was made by an observation when alkali was added to the polymer system. Conclusively, an introduction of alkali results in a shear thinning effect of our fluid meaning that viscosity of the fluid will go down with increasing shear rate. This again supports the early statement of a non-Newtonian fluid behavior. The effect of shear thinning is not quite undesirable for the ASP process, because a water breakthrough while oil production will lead to a reduced value of HC production, and may lead to bypassing

oil .The former effect of a water breakthrough is called a viscous fingering in the petroleum engineering. When testing the effect of polymer/alkali system viscosity with time, we may conclude by observation that viscosity of the system drops graduation. In another words, this viscosity degradation of the system alerts us about time issues should be taken into account.

**Major conclusion**

The conducted experiments proved the efficiency of introduction of the three chemicals such as alkali, surfactant, and polymer to the aqueous system. In particular, alkali and surfactant significantly drops interfacial tension of crude oil leading to increased oil mobilization and sweep efficiency. Polymer addition changes Newtonian fluid to non-Newtonian by increasing viscosity. Polymer greatly builds up an aqueous solution viscously. Addition of alkali to polymer system results in a shear thinning effect.
For a successful Alkali-Surfactant-Polymer flooding, the investigation of crude oil, and reservoir aqueous fluid must be done. Furthermore, all chemical should be tested for an assurance of a compatibility with the reservoir fluid and rock properties.

**Future research**

The very important step which needs to be taken in the future is a coreflood experiment which will incorporate the analysis of rock mineral properties (sandstone or carboinate formation) and aqueous phase (usually salt water) into ASP flood analysis. The coreflood experiment also results in a determination of the potential oil recovery as a ratio of trapped

immovable oil to mobilized oil when injecting alkali, surfactant, and polymer to the system.

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# CONTACT INFORMATION


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| Name: | Darya Musharova |
| Professional Address: | c/o Dr. Hisham Nasr-El-Din<br>Department of Petroleum Engineering<br>Texas A&M University<br>College Station, TX 77843 |
| Email Address: | darya555@neo.tamu.edu |
| Education: | B.A., Petroleum Engineering, Texas A&M University, May 2010<br>Undergraduate Research Scholar<br>Society of Petroleum Engineering Member |